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Near-complete loss of fire-resistant primary tropical forest cover in Sumatra and Kalimantan

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Abstract

Deforestation in Indonesia in recent decades has made increasingly large parts of the region vulnerable to fires. Burning is particularly widespread in deforested peatlands, and it leads to globally significant carbon emissions. Here we use satellite-based observations to assess loss and fragmentation of primary forests and associated changes in fire regimes in Sumatra and Kalimantan between 2001 and 2019. We find that fires did not penetrate undisturbed primary forest areas deeper than two kilometres from the forest edge irrespective of drought conditions. However, fire-resistant forest now covers only 3% of peatlands and 4.5% of non-peatlands; the majority of the remaining primary forests are severely fragmented or degraded due to proximity to the forest edge. We conclude that protection and regeneration of the remaining blocks of contiguous primary forest, as well as

peatland restoration, are urgently needed to mitigate the impacts of potentially more frequent fire events under future global warming.

Introduction

The rates of commodity-driven loss and degradation of primary forests in Indonesia[1,2] have been among the highest in the world over the past five decades[3,4]. The islands of Sumatra and Kalimantan, home to the majority of Indonesia's carbon-rich peatlands, have been particularly affected[5,6,7]. One of the consequences of this rapid change in land use and cover has been a dramatic increase in fire occurrence. In recent decades, the region has experienced recurring extreme peatland burning episodes, most notably the 1997 – 1998[8] and 2015[9] events. These were globally significant greenhouse gas emission events and resulted in extended toxic haze episodes with severe effects on human health and the economy on local and regional scales[10,11]. The two interlinked phenomena of deforestation and peatland fires accounted for half (~0.7 Gt of carbon) of the total annual carbon emissions in Indonesia in the 21st century and pose a challenge for the commitment of the Indonesian government to reduce emissions by at least 29% by 2030[12]. It is widely accepted that the ongoing tropical forest loss is exacerbating this challenge, because deforested land in this region is much more fire-prone[13,14,15]. However, a region-wide assessment of the ability of remaining primary forest to resist fire is currently lacking.

Fire is a rare phenomenon in intact tropical forest ecosystems[13,16]. Closed-canopy tropical forests limit the amount of solar radiation reaching the ground, maintain high humidity in the understorey, and lower temperatures by evaporative cooling on local scales[17,18]. Importantly, tropical forests are able to sustain elevated humidity during prolonged droughts[19] and, as result, act as a protective layer shielding the landscape from the impacts of regional climate variability. While fires episodically did occur in Sumatra and Kalimantan during the Holocene[20,21], they were infrequent and did not cause a long-term loss in the forest vegetation, which covered the majority of the region at least since the end of the Last Glacial Maximum[16,3].

Forest cover has played a particularly important role in the region's peatlands. An estimated 16 to 33 Gt[20,22] of carbon – equivalent to 2 to 4 years' worth of contemporary global fossil fuel emissions – have accumulated in the region's peatlands since the Last Glacial Maximum, forming a peat layer up to 20 metres deep[23]. These peatlands have been a persistent carbon sink for at least the last 20,000 years[24], and in the late Holocene the region has been the most effective carbon sink on a unit area basis globally[20]. Throughout this time, forests were very effective at preventing this important carbon pool from being released into the atmosphere by fires through its regulating effect on climate at local and regional scales.

Reduction in tree canopy cover has a large effect on local and regional climate, and on surface energy balance[25]. Deforested landscapes in Sumatra and Kalimantan have a drier microclimate, experience more extreme temperature events and are substantially warmer[26,27]. Air temperature in selectively logged forests and oil palm plantations is on average up to 2.5 ℃ and 6.5 ℃ higher when compared to nearby undisturbed forests, respectively[28]. In peatlands, increased amounts of solar radiation due to reduced shading affects hydrology and accelerates desiccation and heating of near-surface peat[29], which has low thermal capacity and can be heated rapidly when dry. The increased fire risk is also exacerbated by widespread use of peatland drainage[30], and the establishment of herbaceous and easily flammable vegetation in unmanaged land following forest clearing and recurrent burning[31].

The effects of deforestation on susceptibility to fire are not limited to cleared land, but may extend up to several kilometres into adjacent undisturbed forests[32,33]. The resulting edge effects include increased tree mortality[34], lowered tree reproduction rates[35], and lower biomass when compared to intact forests[36,37]. The fire risk at the forest edges is elevated by canopy desiccation[38], increased temperature and wind[39]. Furthermore, in peatlands, artificial drainage can lower the water table up to 2 km into neighbouring peat swamp forest increasing peat ignitability[40,41].

All the above factors, when coupled with extensive use of fire in human activities[42], result in widespread burning on the converted land during dry periods[43,44,45.], which across the region are influenced by an intricate interplay of large scale interannual climate variability modes. In south

Sumatra and south Kalimantan, prolonged dry periods primarily occur during positive El Nino phase[45,51], while positive Indian Ocean dipole (IOD) phase events have a greater influence on length and severity of dry season in north and central Sumatra[46]. The most severe drought episodes, like the 1997 – 98 event, occurred when both El Ninio and IOD were strongly positive. The region's peatlands are particularly affected, with many areas experiencing recurrent burning during the last three decades[31,47]. Repeated burning and oxidation of carbon due to drainage have therefore resulted in the region's peatlands converting from carbon sinks to sources[48].

While the ongoing primary forest loss[6,4] and associated increase in fire occurrence[49,50,51,5,14,52] in Sumatra and Kalimantan have been highlighted previously, there are no region-wide assessments of the magnitude to which the region has been stripped of the drought and attendant fire protection that primary forests used to provide. Here we present an assessment of loss and fragmentation of primary forest cover combined with fire detections in peatland and non-peatland areas of Sumatra and Kalimantan within the last two decades (2001-2019), in order to identify trends and thresholds relevant to functioning of forests as a fire barrier and protection of peatland carbon stocks in the region. We find that undisturbed primary forest areas located at least 2 km from the forest edge are extremely resilient to fire, but only a small fraction of primary forests remain in this category. As a result, the magnitude of forest degradation and associated increase in high fire risk area is far greater than what the total extent of the remaining primary forests in the region would suggest.

Results and Discussion

Changes in total primary forest extent

Primary forest cover in the Indonesian islands of Sumatra and Kalimantan (Fig. 1), both in the region's peatlands and non-peatlands reduced dramatically in extent between 2001 and 2019 (Fig. 2). At the beginning of year 2001, primary forests covered 45 Mha of the region's total area of 101.5 Mha, whereas at the end of 2018 the cover comprised only 37 Mha. This change equates to average annual primary forest loss of 0.43 Mha. Over half of the total loss occurred in non-peatlands, where primary forest extent was reduced from 39 Mha in 2000 to 33.6 Mha in 2019 (Fig. 2c). Relative change was much larger in peatlands, which cover approximately 11.4 Mha (11%) of the region[53], (Methods). In the year 2000, primary forests covered ~6 Mha or 53% of peatlands. By the end of 2018 the extent was reduced to 3.4 Mha (30% of the area) (Fig. 2b).

During the study period, primary forest loss increased during the first half of the record, peaked in 2012, and gradually decreased afterwards. Notably, during the last two years in the record (2017 and 2018) deforestation has fallen to levels not seen since the 2001 – 2003 period (Fig. 2a). The overall reduction is primarily attributable to a large drop in primary forest loss in peatlands. This may be a sign that the policy changes and incentives in Indonesia such as the peatland restoration plan and moratoriums on primary forest clearing for oil palm plantations and logging operations[65] have begun to improve the situation[66,54]. As a result of this, Indonesia and Norway have agreed on a first payment as part of the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program[55].

Forest fragmentation

While estimates of total primary forest cover indicate a large reduction over the study period, these figures do not reveal the magnitude of degradation to structural integrity of the remaining forests. Our analysis of primary forest percent cover at 1 km resolution illustrates that the ecosystem is increasingly fragmented. The number of 1 km grid cells representing undisturbed primary forests, defined here as grid cells having primary forest cover of 99% or more, has reduced dramatically over the years (Fig. 3). The decrease was particularly strong in peatlands, where the area covered by undisturbed primary forest grid cells has reduced from approximately 32% of peatlands in 2000 to 16% at the end of 2018. Critically, this result shows that at the end of 2018 almost half of the remaining primary forests in peatlands were distributed either as small fragments and/or located close to the forest edge. A particularly large increase was recorded in area covered by mostly-deforested grid cells (50% to 1% cover), both in peatlands and non-peatlands. These dramatic changes have wide-ranging implications for biodiversity[56,57], carbon storage[37] and, indeed, fire occurrence in the region, as demonstrated below.

Primary forest cover and fire occurrence

When estimated for different primary forest cover percentage categories (Fig. 3), the fire-affected area (defined here as % of 1 km grid cells with active fire detections (see Methods)) was notably larger for areas with reduced or completely lost primary forest cover compared with relatively undisturbed closed-canopy forests. In the region's peatlands, fire affected on average only 0.9% of grid cells in undisturbed primary forest category, but 6.2% of partially deforested, 11% of mostly deforested, and 8.3% of completely deforested grid cells each year. In non-peatland areas, only 0.09% of undisturbed forest grid cells experienced fire each year, while fires were present in 1.3%, 3.3%, and 2.1% of the grid cells representing partially, mostly, and completely deforested areas, respectively. In drought years, as much as 22% and 8% of the area was fire-affected in the most vulnerable, mostly, and completely deforested categories in peatlands and non-peatlands, respectively. Meanwhile, in undisturbed forests the highest fire-affected area was 3% in peatlands and only 0.23% in non-peatlands (Fig. 3).

These results illustrate that once the microclimate regulation of the closed-canopy primary forests is lost, the many anthropogenic ignitions in the region[42] often develop into persistent and large burning events during dry periods. The highest fire-affected area on mostly deforested land estimated in this study can be attributed to extensive use of fire as a tool for clearing the land for agriculture in the region[5,58,66]. The tool is very effective because highly fragmented and degraded patches of primary forests contain dead woody fuel and exhibit little ignition-resistance[33] and as a result are easily ignited and consumed by both intentional burning or escaped fires.

Our results indicate that there is a long-lasting increase in fire risk in the deforested landscapes, extending beyond the immediate deforestation period. While areas with fragments of primary forests (between 50% to 1% cover) had the highest percentage of fire-affected grid cells, fire occurrences were nearly as high in land which has been completely deforested (less than 1% primary forest cover (Fig.3)). Although deforestation fires are reduced once the land is fully cleared of primary forests, fire is still used in agricultural practices and as a means to prevent secondary regrowth[58,52]. Degraded and unmanaged peatlands in this region have therefore short fire return intervals and as a result such areas become dominated by flammable grasses and ferns and effectively switch to a stable treeless state[31,14]. While in some managed land cover types, such as large scale oil palm and pulp plantations fire may be undesirable and is actively suppressed, such areas nonetheless have higher fire occurrence rates when compared to primary forests[15].

Overall, the percentage of fire-affected grid cells in peatlands estimated in this study was on average 4.3 times higher when compared with non-peatlands. This signifies the vulnerability of deforested tropical peatland's carbon pool to fire emissions. In peatlands, the fire problem is exacerbated by drainage and desiccation of surface peat which makes it highly combustible[14,47]. Once ignited, the peat layer can sustain underground smouldering combustion for weeks and even months and spread over large area. As a result, the region's peatlands, while representing only 11% of the area, are the source of the majority of smoke emissions during the extreme fire episodes[59].

The increase in fire-prone area over the study years presented in Fig. 3 elucidates how the ongoing primary forest loss has amplified the burning episodes over time. Figure 4, which shows changes in primary forest cover and fire-affected area only for the grid cells which were 99% forested at the beginning of 2002, illustrates this point further. During the study period, half of undisturbed and hence fire-resilient primary forests have been affected by deforestation and transitioned to fire-prone landscapes (Fig. 4b). Although in non-peatlands (Fig. 4c) loss of undisturbed forests since 2001 was smaller in relative terms, the effect was the same – more than a ten-fold increase in the percentage of fire-affected grid cells in areas affected by deforestation. The same pattern was observed across different sub-regions of Sumatra and Kalimantan (Supplementary Figures 1 – 4). The land which has become fire-prone contributed considerably towards the magnitude of the two most recent large fire episodes in the record. Indeed, 15% of total fire-affected area during the 2015 episode did occur on land which experienced deforestation since the year 2002, while the respective figure for the 2019 event is 17%.

While fires overall were rare in grid cells with primary forest cover of more than 99%, they were nonetheless present in undisturbed primary forests, in particular during the years with negative monthly precipitation anomalies (Fig 3a). The analysis of grid cell distance from the forest edge and fire occurrence during the study period (Fig. 4) shows that primary forest grid cells located at the forest edge were much more likely to be affected by fire, and that the vast majority of burning did occur within the first 2 km from the forest edge. While approximately half of the remaining undisturbed forests were located within 1 km from the forest edge, they accounted for 94% and 97% of all fire-affected grid cells in peatlands and non-peatlands respectively. The grid cells located between 1 and 2 km from the edge accounted for further 6% and 3% of the total fire-affected area. Notably, undisturbed primary forests located further from the forest edge than 2 km accounted for less than 1% of total fire-affected area within the forests both in peatlands and non-peatlands, with only a few grid cells experiencing burning during the study period. This demonstrates that the small amount of burning observed in the region's primary forests[51,15] was occurring within the first 2 km from the forest edge, while the inner regions remained virtually fire-free.

A near-absence of burning in the interior of the undisturbed primary forests yet again signifies how resilient to fire this ecosystem is and the role it plays in protecting millennia-aged peat carbon from combustion. The fact that this vanishingly small proportion of the remaining undisturbed forests did not ignite or permit persistent fires to burn into the inner regions (Fig. 4), indicates that in the 21st century these forests were effectively decoupled from the impacts of regional climate variability on fire occurrence. The close association between climate and fire in the region[50,43,45,60] does not seem to apply to primary forests which remain undisturbed and are not compromised by exposure to the edge effects. Extremely low numbers of fire-affected grid cells in such forests recorded during the study period suggests a very long fire return interval. This indicates that in the 21st century, as throughout the Holocene[20,21], fire was not the main driver of deforestation in Sumatra and Kalimantan.

Notably, Fig. 4 also shows that at the end of 2018, undisturbed primary forests located further than 2 km from the edge comprised only ~3% of the region's peatlands and ~4.5% of non-peatlands area. Critically, up to 84% of the peatlands was under high fire risk (less than 99% primary forest cover, Fig. 3b) and an additional 13% was under increased fire risk (undisturbed primary forests within 2 km from forest edge, Fig. 4b). This result also means that only 10% of the remaining primary forests in peatlands in the year 2019 were in the 'resilient to fire' group, while the remaining 90% were either severely fragmented or degraded by the edge effects. During the study years, maximum distance from the forest edge reduced from 11 to 8 km in peatlands, and from 19 to 14 in non-peatlands. The pace of disappearance of the forests which are not exposed to the edge effects in the region may mean that the first two decades of the 21st century provides the last opportunity to obtain satellite-based estimates of fire occurrence in undisturbed primary forests in Sumatra and Kalimantan.

The results demonstrate that the ongoing primary forest clearance in the region has led to substantial growth in the extent of the high fire-risk area, and in the region's carbon-rich peatlands in particular. While forest loss rates in peatlands and associated fires have been relatively low since 2017, we estimate that only a small fraction of the remaining total area of primary forests in the region still function (as they were throughout the Holocene) as a 'layer' that protects the underlying peat from combustion. Of the peatlands in Sumatra and Kalimantan, 97% have now transitioned from being fire-resilient to flammable due to a combination of widespread fragmentation, drainage and the replacement of fire-sensitive rainforest trees with pyrophillic invasive plant species such as ferns and grasses, with severe consequences for local communities, biodiversity, regional air quality and global climate.

Methods

Primary forest loss and extent

In this study, primary forest extent in region for the year 2000 was determined from the primary forest cover dataset based on multi-temporal analysis of Landsat imagery[6,61]. In this product, all Landsat pixels (~25 m x 25 m) with tree height of at least 5 m and canopy cover of > 30% were considered as forest, and primary forest was defined as old-growth natural forest forming a contiguous block of at least 5 ha and which has not been deforested in recent history, including both intact and degraded types[61]. The product was shown to have 90.2% overall agreement (80% Kappa statistic) when compared to the primary forest map for the year 2000 of Ministry of Forestry of Indonesia[6]. In order to determine loss in primary forest cover in Sumatra and Kalimantan during the study period, we performed a co-located analysis of the primary forest cover of the year 2000 data[6] and a subset of the version 1.6 global annual forest cover loss dataset covering 2001 through 2018[62]. In this product, tree cover loss is defined as a stand replacement disturbance. Validation of tree cover loss for tropical regions suggest that forest loss was correctly identified in more than 80% of the cases (producer's accuracy 83.1%)[62].

The analysis of primary forest loss was performed at the Landsat pixel level, replicating and extending in time the study of primary forest loss[6]. Tree cover loss pixels were matched with the primary forest cover dataset pixels to determine if loss was occurring in primary forest or in other tree cover areas. Total primary forest extent for each year was determined by subtracting accumulative primary forest loss leading to the year from primary forest extent in the year 2000. As a result, the derived primary forest cover estimate for a given year represents the state at the beginning of the year. Primary forest loss during that year is accounted for in the estimate for the year after.

The analysis of relationships between primary forest percentage cover and fire occurrences was performed at 1 km resolution. Individual primary forest 25 m pixels for each year were aggregated to derive per 0.01^{o} grid-cell primary forest percent cover. This study uses four different defined categories of primary forest percent cover. Grid cells were classified into one of four categories: 'undisturbed forest' (over 99% primary forest cover); 'partially deforested' (50% < primary forest cover < 99%), 'mostly deforested (1% < primary forest cover < 50%); and 'fully deforested'(<1% primary forest cover). The 99% primary forest threshold in classifying undisturbed primary forests was used in order to allow for a small number of deforestation to occur within a 1 km grid cell (up to 16 out of 1600 25 m Landsat pixels in a 1 km grid cell) before it was reclassified as partially deforested. This was done to accommodate a small amount of natural canopy succession and/or erroneous forest loss pixels. Correspondingly, a 1% primary forest threshold was used in defining fully deforested grid cells. While the selected 99% threshold caused the estimated extent of undisturbed primary forests to be approximately 20% larger when compared to a scenario when a strict 100% threshold was used, this only had a negligible effect on fire occurrence rates for the category. However, lowering the threshold further resulted in a large increase in fire detections in undisturbed primary forests, hence a 99% threshold was used.

Distance to the forest edge

Distance to the forest edge was computed for all undisturbed primary forest grid cells (cover >99%). For this purpose, any grid cells with less than 99% primary forest cover were considered to be non-forest. Distances were derived in a way that all primary forest grid cells adjacent to non-forest grid cells (8-connected neighbourhood) were classed as areas within 1 km from the edge.

Fire affected areas

As a proxy for fire activity, the study used Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 fire locations (MCD14ML) dataset, produced by the University of Maryland and provided by NASA Fire Information for Resource Management System. The product contains centre coordinates of MODIS pixels (1 km^2 for areas directly below, up to ~10 km^2 in area at the extreme edges of the sensor view) flagged by the MODIS Thermal Anomalies algorithm[63]. The product has estimated 8% false detection rate for South Asia, and less than 10% omission error for fires of over 0.125 km^2 globally[63]. To reduce the commission error further, low confidence (<30%) detections were excluded from the analysis.

Fire-affected area was used as a proxy for fire activity. Using this approach, any 1 km grid-cells containing any number of active fire detections within any given year were flagged as fire-affected. In order to identify areas affected by large and persistent burning events, single active fire detections which were not part of bigger events were filtered out. This was achieved by agglomerating any individual active fires located closer than 3 km in space and less than 48 hours in time. Following this step, only active fire detections which were part of fire events which were observed on at least two different days were selected for further analysis. This additional filtering step resulted in 12% and 45% reduction in total active fire detections in the region’s peatlands and non-peatlands respectively. The difference in reduction indicates that a larger proportion of active fire detections in non-peatlands is a record of small fires which do not develop into persistent burning events. This filtering step also brought the estimate of percentage of total fire-affected area attributable to peatlands up to ~40%, which is in the range of estimates obtained by other studies employing MODIS area-burned products and estimates based on different sensor data[64].

Peatland areas

In order to differentiate between peatland and mineral soils (non-peatland) areas the study utilized the high-resolution maps of Indonesian peat distribution and carbon content published by Wetlands International and Wildlife Habitat Canada[53]. The vector dataset was rasterized to 1 km resolution grid. Rasterization was applied in a way that any grid cells whose centre point was inside the peatlands polygons was considered to represent peatland areas. As a result, the total peatlands extent determined in this study is ~10% smaller than that derived directly from the source dataset.

Precipitation anomalies

This study used European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 0.25^{o} global reanalysis precipitation dataset for deriving monthly precipitation anomalies in the region for the study period. The anomalies shown in figures 3 and 4 represent difference between mean precipitation for all land ERA5 grid cells over Sumatra and Kalimantan for any given month and climatic monthly mean precipitation for the 2002 – 2019 period.

Data availability

All datasets used in the study are publicly available. Primary forest cover in year 2000 is available at: https://glad.umd.edu/dataset/primary-forest-cover-loss-indonesia-2000-2012. The annual forest loss data available on-line from: http://earthenginepartners.appspot.com/science-2013-global-forest. Active fire data can be downloaded from: https://firms.modaps.eosdis.nasa.gov/download. Peatland extent maps are available at: http://data.globalforestwatch.org/datasets. ERA5 reanalysis dataset can be downloaded from: https://climate.copernicus.eu/climate-reanalysis. The annual primary forest % cover and active fire detection counts at 1km resolution datasets generated by this study can be accessed at http://doi.org/10.5281/zenodo.4199924.

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Author contributions

T.N. and A.S. designed the study with input from S.H.D. T.N. performed the analyses and wrote the initial paper. A.C.S, S.H.D., G.D.C. and S.M. contributed to interpreting the results and writing the final paper.

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Competing interests

The authors declare no competing interests.

Figure captions

Fig. 1: The remaining fire-resilient primary forests in Sumatra and Kalimantan.

Primary forest % cover the regions peatlands (orange through red) and non-peatlands % (green through blue) at the beginning of 2019. The categories shown are <99% primary forest cover, primary forest cover >99% but within 2 km from the forest edge, and primary forests cover >99% and further from the forest edge than 2 km.

Fig. 2: Changes in total primary forest cover in Sumatra and Kalimantan from 2001 through 2018

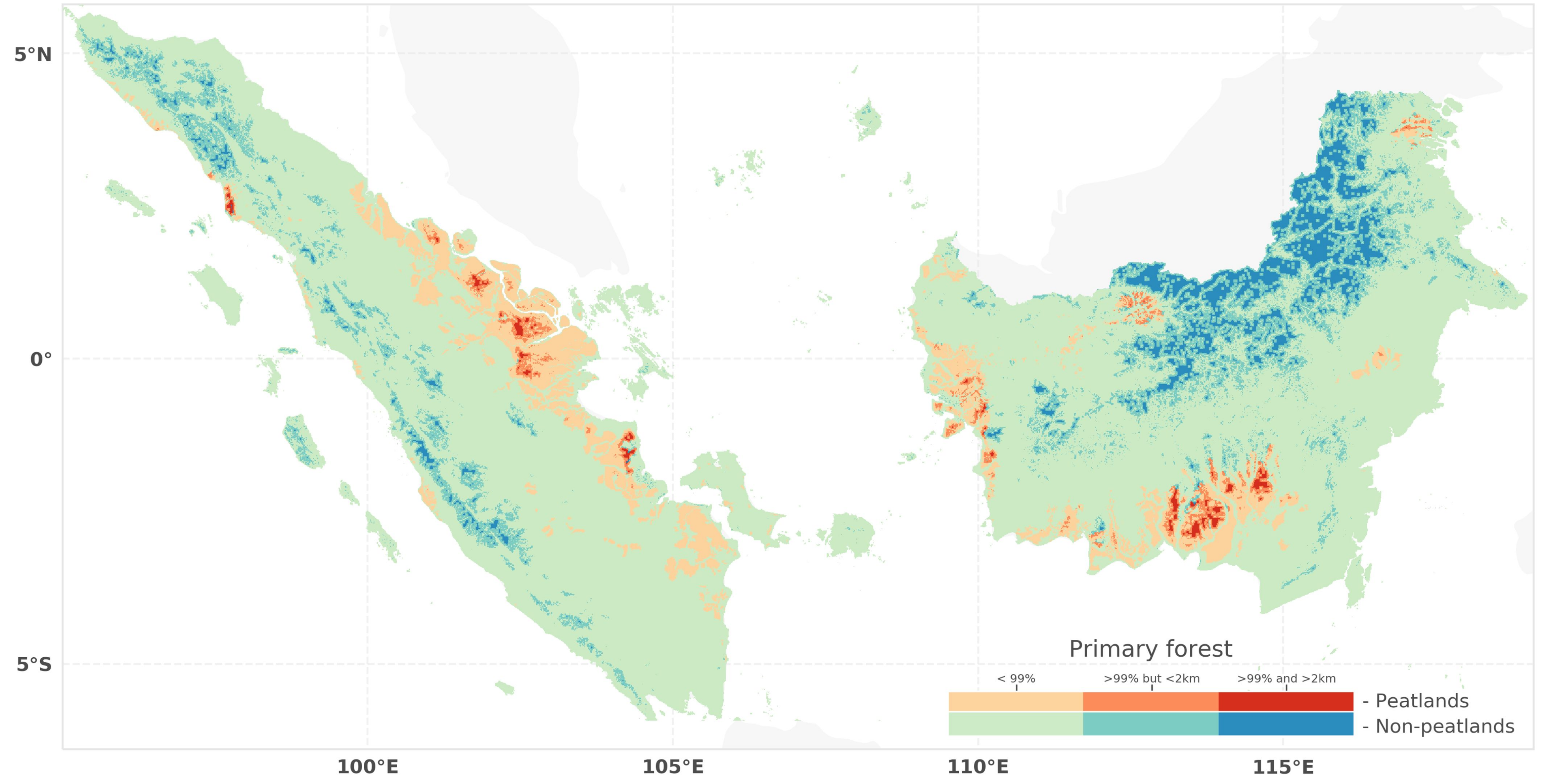
a) Annual primary forest cover loss in the region; and total primary forest cover at the beginning of 2001 and 2019 shown against total area of (b) peatlands and (c) non-peatlands.

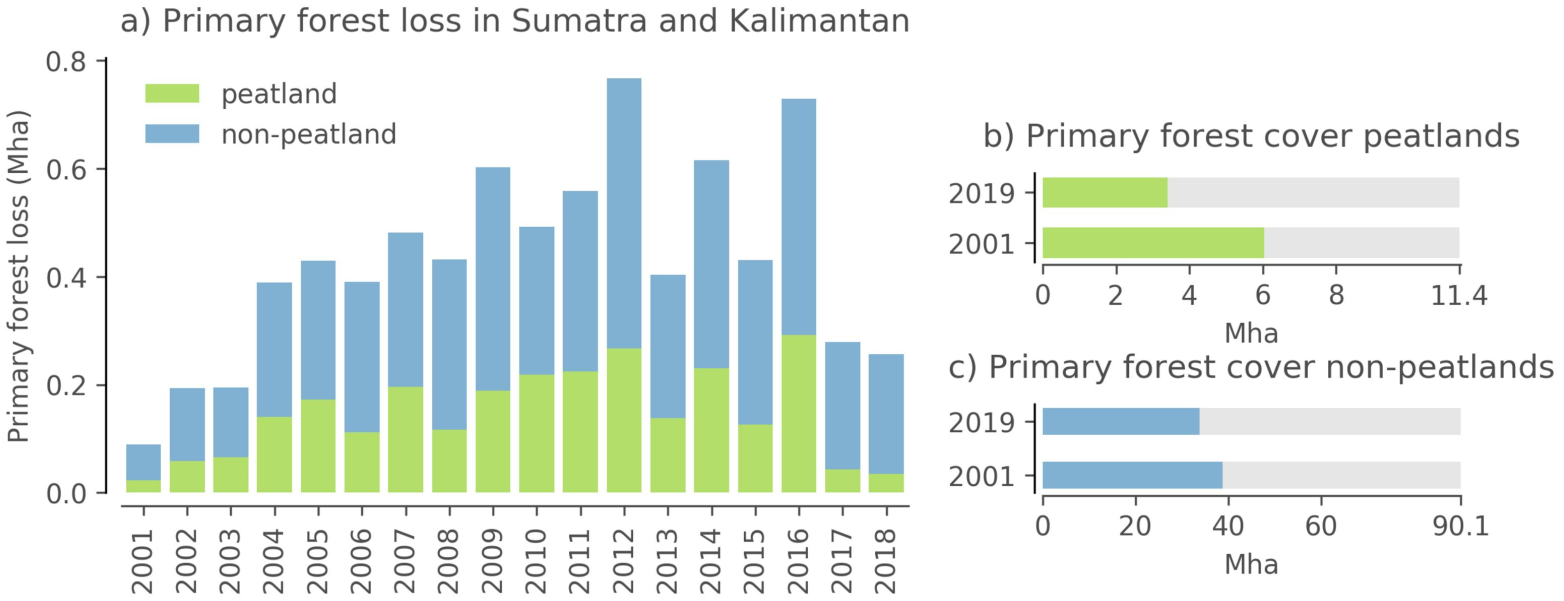
Fig. 3: Primary forest cover and fire occurrence in the region.

a) Monthly precipitation anomalies in the region for the study period (Methods). b, c) Change in extent and % of fire-affected grid cells for different primary forest cover percent categories in peatlands (b) and non-peatlands (c) of Sumatra and Kalimantan. The grey lines represent primary forest cover thresholds and indicate year to year changes in extent of areas covered by 1 km grid cells having primary forest cover of more than 99% (area to the left from the 99% threshold line), 99% to 50%, 50% to 1% and less than 1%. Colour indicates % of fire-affected grid cells. Primary forest cover estimates for each year represent the state at the beginning of the year. Forest loss estimate for that year is accounted for in the figure for the following year.

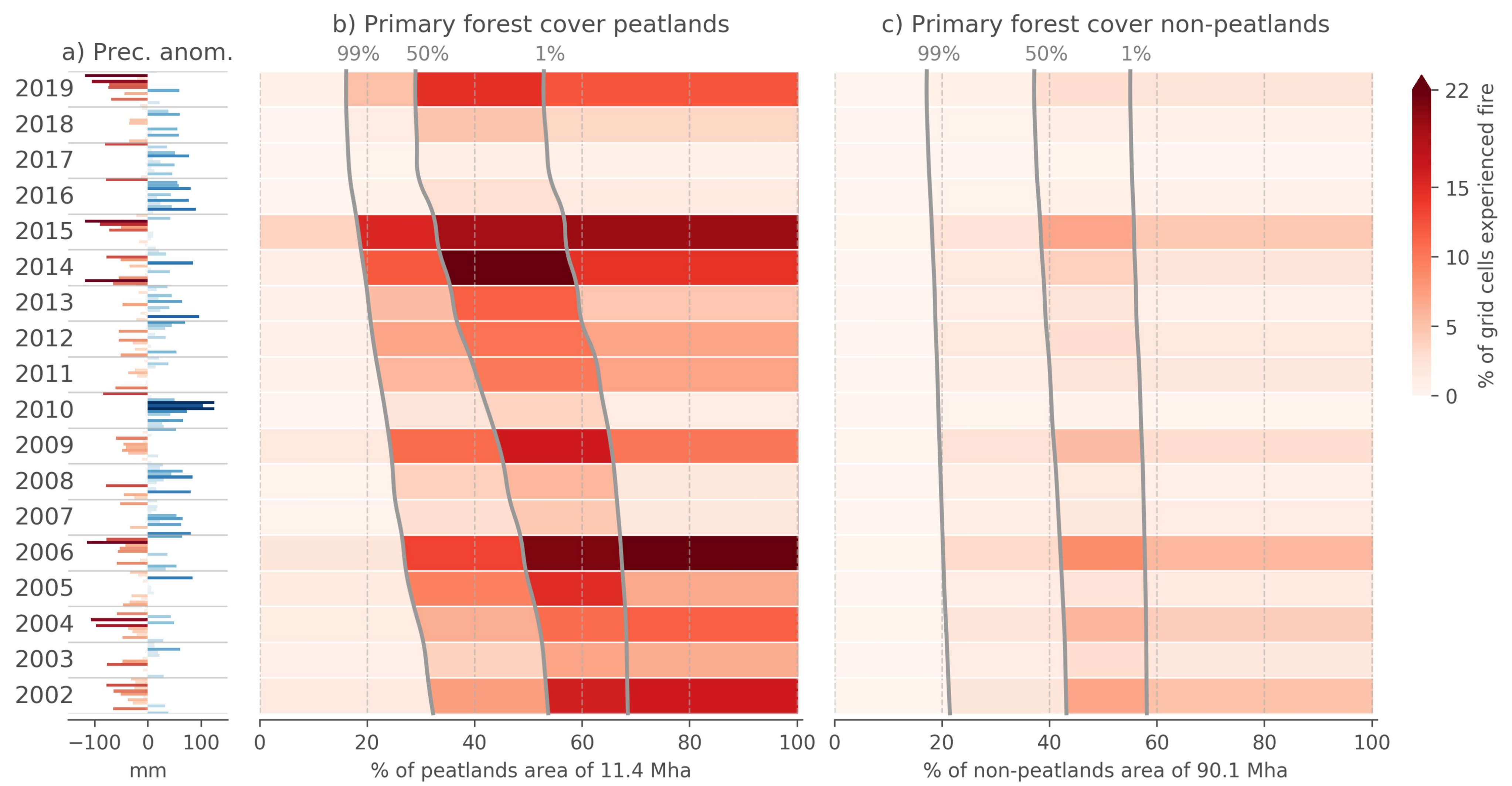
Fig. 4: Changes in forest cover and fire occurrence in areas which were >99% primary forests in the year 2002.

a) Monthly precipitation anomalies in the region for the study period (Methods). b, c) Change in extent and % of fire-affected grid cells. In contrast to Fig. 3, this Figure only shows (b) peatland and (c) non-peatland areas which were undisturbed primary forest (grid cells having 99% or more primary forest cover) at the beginning of year 2002. Solid grey lines indicate the primary forest cover percentage thresholds as in Fig. 3. Dashed grey lines represent distance from the forest edge thresholds for the undisturbed forest category. Note different colour scales for peatland (b) and non-peatland (c) plots. See Supplementary Figures 1 – 4 showing the same analysis split into different sub-regions of Sumatra and Kalimantan.

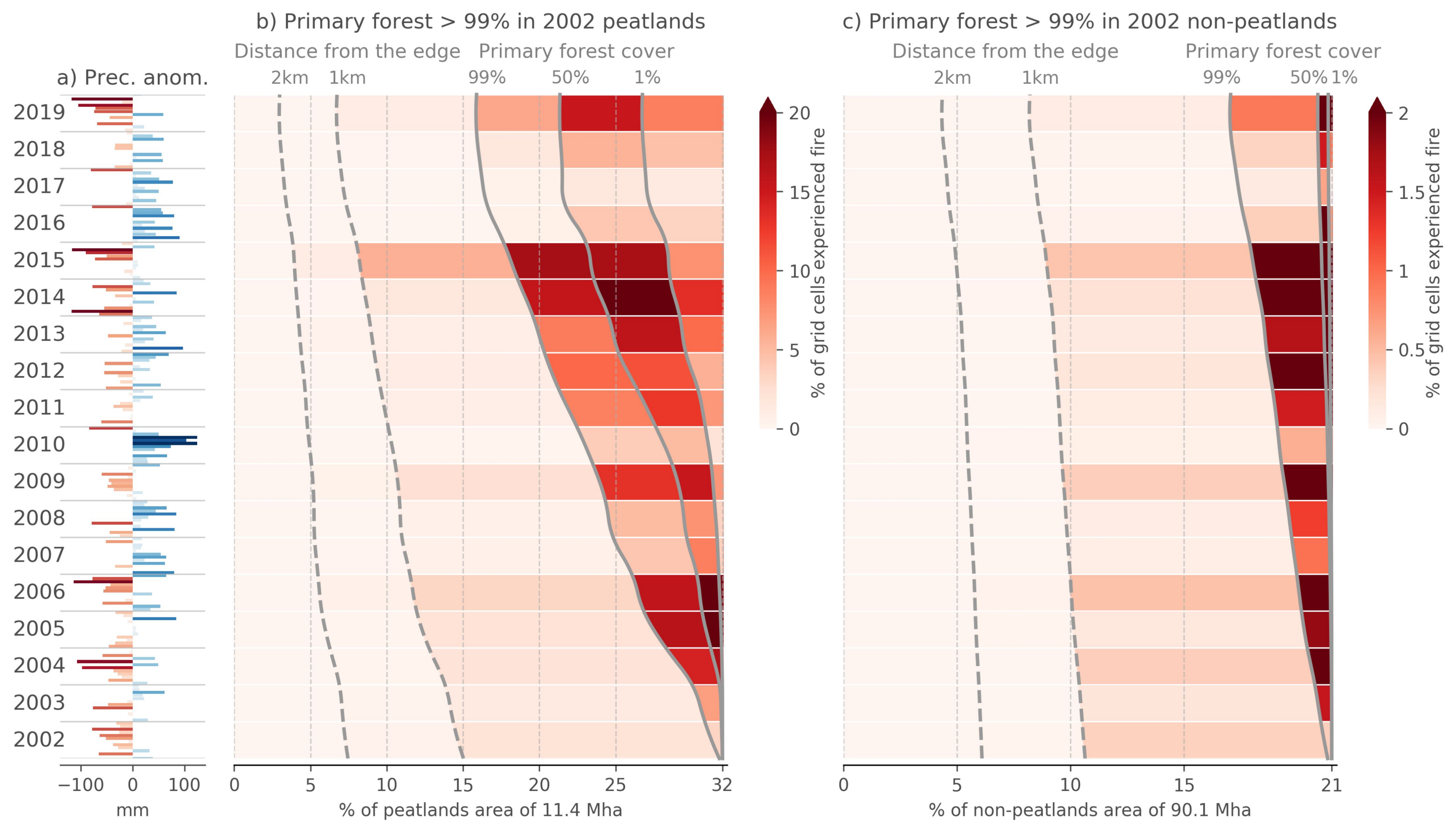

5°N
0°
5°S
100°E
105°E
110°E
115°E
Primary forest
< 99%
>99% but <2km
>99% and >2km
- Peatlands
- Non-peatlands



a) Primary forest loss in Sumatra and Kalimantan
Primary forest loss (Mha)
0.0
0.2
0.4
0.6
0.8
peatland
non-peatland
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
b) Primary forest cover peatlands
2019
2001
0
2
4
6
8
11.4
Mha
c) Primary forest cover non-peatlands
2019
2001
0
20
40
60
90.1
Mha



a) Prec. anom.
b) Primary forest cover peatlands
c) Primary forest cover non-peatlands
99%
50%
1%
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
−100
0
100
mm
0
20
40
60
80
100
% of peatlands area of 11.4 Mha
% of non-peatlands area of 90.1 Mha
% of grid cells experienced fire
22
15
10
5
0


a) Prec. anom.
b) Primary forest > 99% in 2002 peatlands
c) Primary forest > 99% in 2002 non-peatlands
Distance from the edge
Primary forest cover
2km
1km
99%
50%
1%
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
−100
0
100
mm
0
5
10
15
20
25
32
% of peatlands area of 11.4 Mha
0
5
10
15
21
% of non-peatlands area of 90.1 Mha
% of grid cells experienced fire
20
15
10
5
0
2
1.5
1
0.5
0